4D visualization of isotropic turbulence and dynamics of high-enstrophy structures

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1 Introduction

It is well known that in the high Reynolds number turbulence there exist thin tube-like vortical structures whose radii are order of the Kolmogorov length scale. Direct numerical simulations have been successful in revealing their various features (see e.g. Ishihara et al.[1]). Although statistics of turbulence is extensively investigated, there are less works on the geometry and dynamics of the vortical structures. Moisy and Jiménez[2] characterized the geometry and spatial distribution of high-vorticity regions by means of box-counting methods. Bermejo-Moreno et al.[3] extracted structures of high enstrophy and characterized them by geometrical analysis; distribution of blob-like, tube-like and sheet-like structures was studied in some detail. The results so far, however, are mostly based on either instantaneous or averaged fields. The dynamics or temporal evolution of the fine-scale vortical structures remains unexplored.

In this paper we study the dynamics of high-enstrophy structures in isotropic turbulence by 4D visualization and geometric analysis. Our aim is to understand the temporal evolution of vortical structures in turbulence and thereby elucidate the interaction of vortical structures, which includes deformation, reconnection, merging and cancellation; these should play an important role in the cascade process of turbulence. We are particularly interested in the dynamical equilibrium of the fine-scale vortical structures, which is closely related with the statistical properties turbulence and would be helpful in improving the accuracy of turbulence models.

2 4D visualization

The numerical method is essentially the same with Ishihara et al.[4]. The three-dimensional Navier-Stokes equations are solved by Fourier spectral method. The total number of modes is $N^3 = 1024^3$. The microscale Reynolds number is $Re_\lambda \approx 358$, while the Kolmogorov length is $k_{\max}\eta \approx 1.59$ where $k_{\max} = 483 \approx \sqrt{2}N/3$ is the maximum wavenumber.

The DNS data are visualized by Realization WorkSpace (RWS) of the Advanced Fluid Information Research Center (AFIRC), Institute of Fluid Science, Tohoku University. RWS is a virtual reality system for three-dimensional visualization (Fig. 1); the screen extends both in front and on the floor with total size of 4.5[m]×4.0[m]. The large disk space of AFIRC allows us to store a sufficient number of data for animation of the three-dimensional field (4D visualization). In the present study we choose an isosurface of the magnitude of vorticity for the three-dimensional field. The 4D visualization has shown various ways of interaction of the tube-like vortical structures: deformation, reconnection, merging, cancellation etc. This led us to investigate the temporal evolution of the tube-like vortical structures, which are called high-enstrophy structures in the following to make it clear that vortical structures with small magnitude of vorticity are excluded.

3 Analysis of high-enstrophy structures

In order to study the temporal evolution of vortical structures in turbulence, we introduce a simple definition of high-enstrophy structures. First we choose a threshold ω_c for the magnitude of vorticity. Two grid points are said to be *neighbors* if the distance between them is smaller than $2\Delta x$, where $\Delta x = 2\pi/N$ is the grid spacing. Two grid points are regarded as *connected* if there is a sequence of neighbors between them. Then a set of connected grid points S is called a *high-enstrophy structure* if $\omega(\boldsymbol{x}) > \omega_c$ for all $\boldsymbol{x} \in S$. There are a few disadvantages due to the simplicity of the definition. For instance, there are many tiny structures consisting of a few points; one third of the structures have points less than 10. The above simple definition, however, is preferred for the present purpose since it is not time-consuming for temporal analysis.

As a first step toward studying the temporal evolution we show some basic properties of high-enstrophy structures in an instantaneous field of isotropic turbulence. Figure 2 shows the volume fraction of the largest high-enstrophy structure, or in other words, the maximum volume of the structures divided by the total volume of the structures for ω_c. Here the volume is defined by the number n of points in the structure multiplied by the volume of unit cell $(\Delta x)^3$. For small ω_c the largest structure occupies almost the whole region of $\omega > \omega_c$; in other words the whole region $\omega > \omega_c$ is almost connected. A transition is observed between $1 < \omega_c/\overline{\omega} < 3$. For large ω_c the volume fraction is close to zero, which implies that we can identify disconnected high-enstrophy structures. Also shown in Fig. 2 is the number of high-enstrophy structures. It takes maximum around $\omega_c/\overline{\omega} = 1.8$, for which the volume fraction is 0.78, a rather large value. In the following we set $\omega_c/\overline{\omega} = 3$.

Figure 3 shows examples of high-enstrophy structures obtained by the present method. There are a number of tube-like structures like the one shown in left. However, some are combination of such tube-like structures which are interacting as shown in right.

Relation between the volume and area of the high-enstrophy structures is shown by scatter plot in Figure 4. The area is approximately proportional to the number

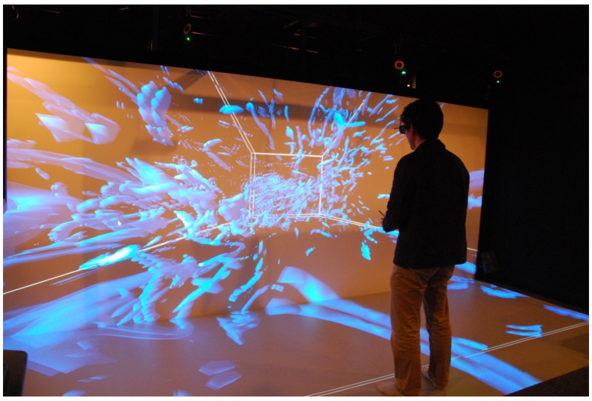

Fig. 1. 4D visualization in Realization WorkSpace.

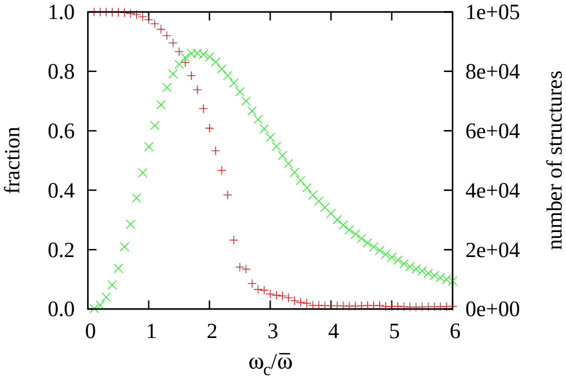

Fig. 2. Volume fraction of maximum high-enstrophy structure (+, left axis) and number of high-enstrophy structures (×, right axis).

n_s of surface points of the structure, where a point in S is called a *surface point* of S if at least one of the adjacent points is out of S. Although the data points are widely spread, we observe a crude scaling law $n_s/n \propto n^{-1/6}$. If we apply this scaling to cylindrical tubes, the radius and the length scale as $n^{1/6}$ and $n^{2/3}$, respectively. The value of the radius is estimated as $r \sim 2(n/n_s)^{1/2}\Delta x$, the maximum of which is $\sim 3\Delta x$. The length is also estimated as $l \sim n_s \Delta x/(4\pi) \sim 10^2 \Delta x$ for $n_s \sim 10^3$. These values are consistent with thin tube-like vortical structures although not all of the high-enstrophy structures are tube-like.

4 Conclusion

The high-enstrophy structures in isotropic turbulence are investigated by 4D visualization using a virtual reality system. As a step toward studying in detail the dynamics of the high-enstrophy structures geometrical analysis of an instantaneous field is performed. Our simple definitions are successfully applied to identify the high-enstrophy structures and their surfaces. Temporal evolution and interaction of the structures are currently investigated and the results will be reported in the conference.

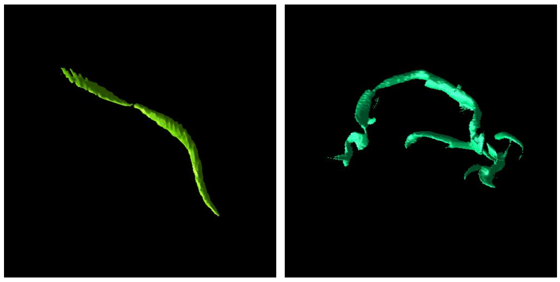

Fig. 3. Examples of high-enstrophy structure.

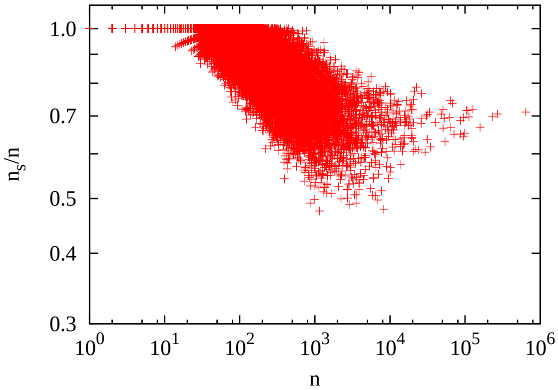

Fig. 4. Scatter plot of n and n_s/n.

Acknowledgment

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